

SAR product improvements and enhancements – SARprises –

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LONG-TERM GOALS

The long-term goal of this project is to utilize the recently established ordering, receiving, and processing capabilities for TerraSAR-X along-track interferometric synthetic aperture radar (along-track InSAR, ATI) data at the University of Miami's Center for Southeastern Tropical Advanced Remote Sensing (CSTARS) for the development of advanced ATI data products, such as surface current fields in narrow rivers, and innovative higher-order data products characterizing, for example, the bathymetry in coastal areas, properties of oceanic internal waves, and the ocean surface wave spectrum, as derived from amplitude signatures, interferometric phase signatures, and polarimetric signatures.

OBJECTIVES

Within the project period of 36 months (which started in spring 2011), we intend to

- ▶ acquire and analyze a comprehensive set of ATI images of rivers, coastal areas, and open-ocean features such as internal waves and tropical storms;
- ▶ explore possibilities of obtaining surface current estimates for challenging test sites, such as very narrow rivers (width < 100 m), where most of the backscattered power from a fast-moving water surface may be mapped into pixels on land;
- ▶ test techniques for two-dimensional vector current field retrievals from combined TerraSAR-X / TanDEM-X along-track InSAR data or combined single-instrument along-track InSAR data from ascending and descending overpasses of a test site;
- ▶ develop tools for the generation of higher-level data products from along-track InSAR-derived surface current fields, such as bathymetric maps of coastal waters and volume flow / mean runoff estimates for rivers of uncertain depth; and
- ▶ evaluate the potential of innovative InSAR- and polarimetry-based techniques for fully two-dimensional surface wave retrievals.

These activities will make significant contributions to an improved understanding and an optimal exploitation of the potential of existing and future spaceborne SAR systems for U.S. Navy operations and for a variety of research and engineering applications.

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APPROACH

The project consists of six main Work Packages, which are defined as follows.

Work Package 1: CSTARS Upgrades. When the proposal was written, we were planning to implement receiving and processing capabilities for TanDEM-X and COSMO-4 at CSTARS (in addition to existing capabilities for other satellites) and to evaluate the ATI capabilities of COSMO-4 and RADAR-SAT-2.

Work Package 2: Data Acquisition and Raw Data Processing. This Work Package comprises the collection and processing of a variety of innovative data sets through CSTARS, including new ATI images of several rivers of different widths, of coastal areas with a strong bathymetry-modulated tidal flow, test areas with internal waves and eddies; dual-beam ATI data from TerraSAR-X and TanDEM-X together for vector current retrievals; and combined along-track / cross-track InSAR and polarimetric data of rivers and ocean scenes for a variety of tests. Some data products were already in the TerraSAR-X / TanDEM-X archives of DLR, acquired during the TerraSAR-X Dual Receive Antenne (DRA) mode campaign and the TanDEM-X commissioning phase in 2010.

Work Package 3: Advanced Current Retrieval Techniques. In this work package we will improve our current retrieval capabilities by testing current retrievals over new kinds of features, such as oceanic internal waves, and by developing techniques for narrow rivers and for two-dimensional vector current retrievals. Due to the azimuthal displacement of moving targets in SAR images, most of the signal contributions from narrow water surfaces may be mapped into pixels on land. They must be separated from the contributions of stationary targets and moved back to the correct location in the image to permit meaningful current estimates. We will try an approach that combines advanced interferometric processing of the two original complex SAR images with physics-based statistical modeling of the contributions from water and land and our existing current retrieval procedure for the correction of SAR imaging artifacts and wave contributions over open waters. Two-dimensional vector current retrievals may be obtained by combining data from ascending and descending overpasses, but a more promising development is based on the idea of simultaneous ATI data acquisitions by TerraSAR-X and TanDEM-X with slightly different look directions. To acquire such data, one of the satellites must be rotated by some angle for a limited time. A demonstration of the dual-beam ATI technique with an airborne system was given Toporkov et al. [1]. Other ideas to be attacked within this Work Package are the combined use of TerraSAR-X and TanDEM-X to cover a larger effective swath or to improve the data quality within the normal swath; multi-baseline along-track interferometry; and a comparison of current fields retrieved from ATI data with results of the Doppler centroid method based on conventional single-channel SAR data (see [2] for an example).

Work Package 4: Advanced Wave Retrieval Techniques. Wave retrieval algorithms for conventional, interferometric, and polarimetric SAR data will be implemented and applied to images acquired in Work Package 1. Results will be compared with each other, with buoy data, and with wave spectra from numerical wave model (WAM) runs. Techniques for combining results of different wave retrieval methods (e.g. based on intensities and phases of interferometric data or on intensities and polarimetric coherences of polarimetric data) will be tested, and the feasibility of phase-preserving wave field retrievals and the detection of freak waves will be evaluated. Combining TerraSAR-X and TanDEM-X data with a short time lag, a retrieval of frequency-wavenumber spectra may be possible. Conclusions regarding optimal wave retrieval strategies and desirable instrument and algorithm improvements for further improved wave retrieval capabilities will be drawn.

Work Package 5: Higher-Level Data Products. The retrieval of bathymetric maps from ATI-derived current fields, requiring only a small number of known depths for deriving a characteristic current-depth relationship for each test area, has been demonstrated in [3]. This existing algorithm will be developed a little further in such a way that it can be applied to new test sites without case-specific optimization and that phases and intensities of ATI images can be analyzed together. Furthermore, visible wave refraction patterns will be included in the analysis. Here we need to account for the dependence of wave signatures in SAR images on the imaging geometry and for effects of SAR imaging artifacts such as velocity bunching. In addition to wave refraction due to changes in the water depth and the corresponding wave velocity according to the shallow-water dispersion relation, some contribution to the modulation of wavelengths and directions of propagation may result from wave-current interaction. We think this contribution can be identified and taken into account in the data interpretation if wave trains propagating in different directions are considered. Furthermore, wave patterns in SAR images acquired at different tidal phases will be subject to different tidal current fields, but a constant bathymetry. At the end of the data processing chain, consistent bathymetric maps should be obtained from all images. In addition to the bathymetry work, an algorithm for river volume flow estimates will be implemented, based on methods discussed in [4] and [5], and techniques for separating tidal contributions from the mean river runoff will be tested on the basis of available long time series of ATI images of rivers. Furthermore, the use of along-track and cross-track InSAR data from TerraSAR-X and TanDEM-X for combined surface current and water level measurements and corresponding improved volume flow estimates will be tested.

Work Package 6: Dissemination. Results of the project will be disseminated through a project website, presentations at international conferences, and publications in peer-reviewed journals. To ensure an efficient collaboration and data exchange with existing ONR program teams and other potential partners and users, we will contact these colleagues in an early stage of the project, inform them about our objectives, plans, and needs, and establish sustainable communication links.

WORK COMPLETED

Work Package 1: CSTARS Upgrades. The implementation of new receiving capabilities at CSTARS was almost completed before this project started. Software upgrades for a complete processing of TerraSAR-X and TanDEM-X ATI products at CSTARS were completed in early 2012. We are currently testing additional software improvements that will go beyond the capabilities of the standard TerraSAR-X data processing package that is implemented at CSTARS. The final version of COSMO-4 does not have ATI capabilities, thus there is nothing to be tested with COSMO satellites within this project. Furthermore, it is not very likely that we will be able to obtain RADARSAT-2 ATI data within the framework of this project because RADARSAT does not make such data available to regular customers.

Work Package 2: Data Acquisition and Raw Data Processing. We have acquired a number of new ATI images from TerraSAR-X and TanDEM-X in 2012, focusing on the New River inlet (relevant for another ONR-funded project) and several test sites where the along-track baseline between TerraSAR-X and TanDEM-X was suitable for current measurements for a limited time in February and March 2012, due to a special orbit constellation. For the first time, these special data acquisitions allowed for current measurements by ATI at near-optimal baselines on the order of 25-40 meters. First results obtained for a test site at Orkney, Scotland, are quite impressive. Examples are shown in the figures at the end of this report. A manuscript for a peer-reviewed journal is in preparation. In addition to these newly acquired data, we have obtained a number of interesting datasets from the TerraSAR-X DRA mode cam-

paign in 2010. This includes two ATI images of internal waves at Dongsha (South China Sea). We also have TerraSAR-X ATI images that show clear phase signatures of surface wave motions, as well as TerraSAR-X / TanDEM-X image pairs from the TanDEM-X commissioning phase with particularly long time lags (too long for interferometry, but they should be suitable for surface current vector retrievals from wave pattern shifts). We will acquire further TerraSAR-X ATI data of relevant test sites in 2013.

Work Package 3: Advanced Current Retrieval Techniques. One important achievement in this task is the successful retrieval of currents over an internal wave at Dongsha from a TerraSAR-X DRA mode image. To our knowledge, this has not been done with satellite data before. Some results are shown in the figures at the end of this report, and a manuscript for a peer-reviewed journal will be finalized soon (this has been delayed because we were hoping to obtain additional reference data). Furthermore, we have developed advanced filtering techniques to remove wave signatures from high-quality phase images obtained with a long along-track baseline (see Work Package 2) and to exploit the wave information for improved corrections. We will soon begin to develop a new current retrieval technique that will be based on spatial shifts in wave patterns in image pairs from the TanDEM-X commissioning phase, with a time lag on the order of 3 seconds.

Work Package 4: Advanced Wave Retrieval Techniques. We do have polarimetric images of waves from the TerraSAR-X DRA mode campaign, but we have not started to work on this work package so far.

Work Package 5: Higher-Level Data Products. We have started to analyze wave patterns in a TerraSAR-X spotlight SAR image to test our ideas about bathymetry retrievals from wave refraction patterns. The results obtained so far are promising. We will try to apply the same technique to ATI data and to combine it with the analysis of spatially varying current fields over bathymetry. This will be the main research topic of graduate student Conor Smith, who started to work in this project in fall 2012.

Work Package 6: Dissemination. We have presented results of this project at an ESA meeting on current measurements in Brest, France, at SeaSAR 2012 in Bergen, Norway, and at IGARSS 2012 in Munich, Germany. Two manuscripts on current fields over internal waves and current fields at Orkney, Scotland, will be submitted to peer-reviewed journals (possibly *Science* for the internal wave manuscript) within the next few weeks. We will continue to present project results at conferences in 2013, such as IGARSS in Melbourne (Australia).

RESULTS

The results obtained so far indicate that it is feasible to obtain direct measurements of the current variations over an oceanic internal wave from TerraSAR-X ATI data. This permits much more robust estimates of internal wave amplitudes and, thus, pycnocline depths etc. than methods based on radar intensity signatures, since ATI signatures are much less difficult to model and less sensitive to uncertainties in wind estimates (discussed for intensity signatures in [6]). Furthermore, we have demonstrated the potential of spaceborne ATI with baselines on the order of 25-40 meters to measure currents and even wave motions with very high spatial resolution. Some further innovative ideas will be tested in 2013.

IMPACT/APPLICATIONS

Our new algorithms will permit current and wave retrievals under conditions where they have not been possible before (e.g. current retrievals in narrow rivers, wave retrievals in regions with dominant azimuth-traveling waves) and / or with significantly improved accuracy. The algorithms for higher-order products will facilitate the use of SAR data for a variety of applications and lead to a better utilization of existing spaceborne SAR capabilities for routine applications. The demonstration of high-resolution current measurements with longer baselines may help to pave the way towards dedicated spaceborne ATI systems for ocean and river applications that could be launched within the next 10 years.

RELATED PROJECTS

All ONR-funded research projects dealing with remote sensing of rivers, tidal flats, and current features and wave spectra in the open ocean, as well as related U.S. Navy operations, can benefit from this project. The project has particularly strong connections to the ongoing "Tidal Flats Dynamics" DRI, in which CSTARS and the PI of this project are directly involved, and to the River Inlet (RIVET) projects.

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PUBLICATIONS

None so far (two will be submitted for publication soon).

PATENTS

None.

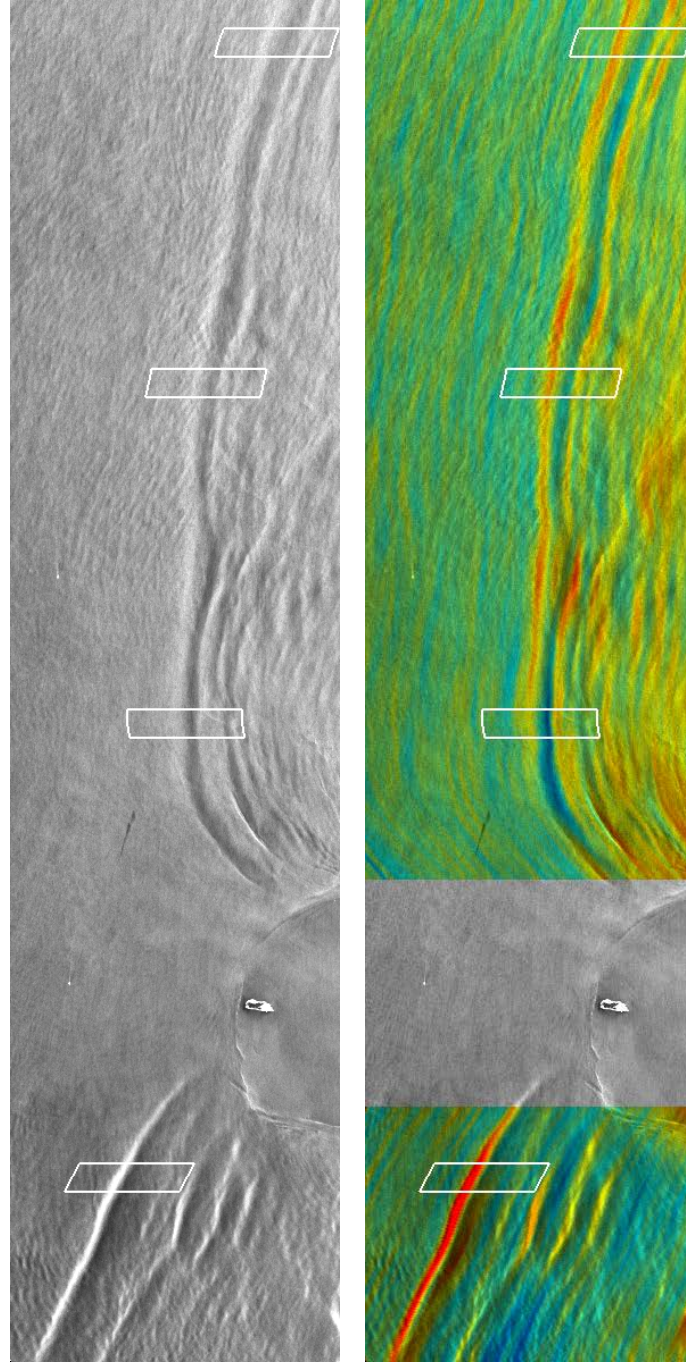


Fig. 1: TerraSAR-X ATI image of internal waves at Dongsha (South China Sea), averaged on a $100\text{ m} \times 100\text{ m}$ grid, trimmed to approx. $29\text{ km} \times 120\text{ km}$. The left-hand part of the figure shows SAR image intensities with a logarithmic grayscale. The right-hand part shows the same with superimposed ATI-derived line-of-sight Doppler velocity variations in color. Flight direction is 191° (here: top to bottom), look direction 281° (here: right to left). Color scale: Red = 0.5 m/s to left, Blue = 0.5 m/s to right. White frames indicate areas for which intensity and velocity profiles have been derived. Note that large image intensities over the internal waves are strongly correlated with large Doppler velocities in the propagation direction.

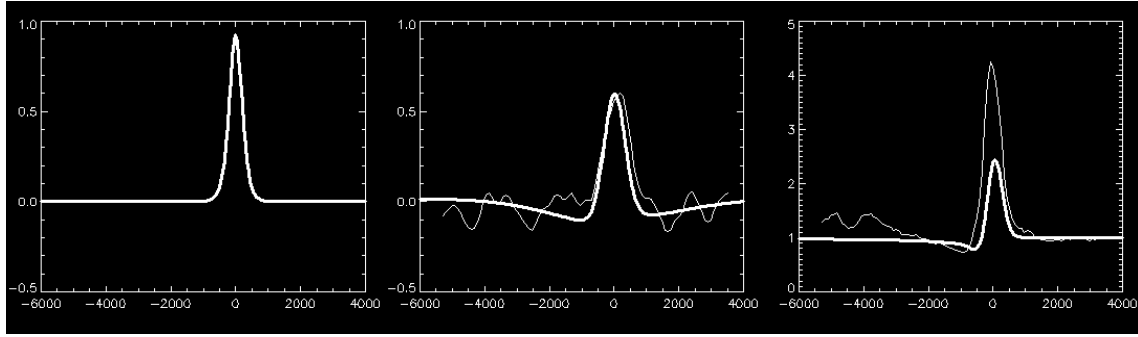


Fig. 2: Preliminary result of simulations of the internal wave signature at the bottom of the image. The diagram on the left shows the surface current field of a possible internal wave in the test area, parameterized such that good agreement between ATI-derived and numerically simulated Doppler velocities is obtained. The center diagram shows the model result as a bold line and the measured Doppler velocity profile as derived from Fig. 1 as a thin line. The agreement is good for a peak surface current on the order of 0.9 m/s (approx. 0.7 m/s in the Doppler velocity). The diagram on the right shows that the strong image intensity modulation of this signature cannot be reproduced by our numerical SAR / ATI imaging model; the same has been found in other applications of the model to scenarios with very strong image intensity signatures.

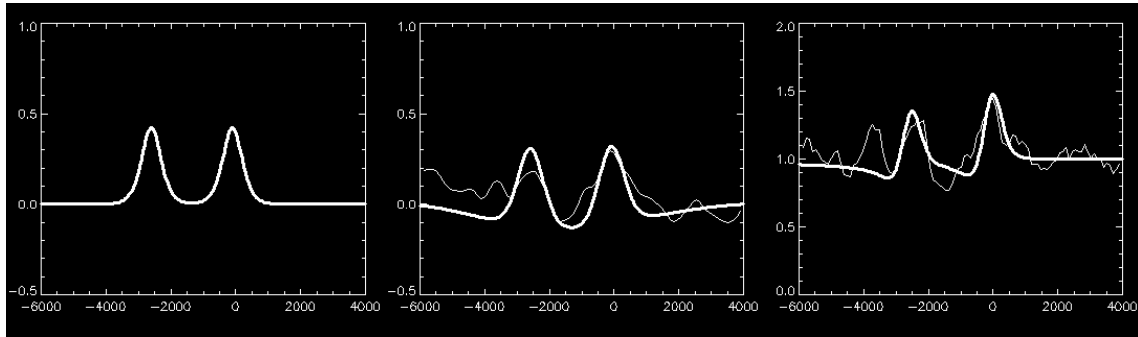


Fig. 3: Same as Fig. 2 for the second white box from the top in Fig. 1. In this case we obtain good agreement of ATI-derived and simulated Doppler and image intensity signatures. Here we have simulated the first two solitons of the internal wave train to obtain a realistic current gradient behind the leading soliton.

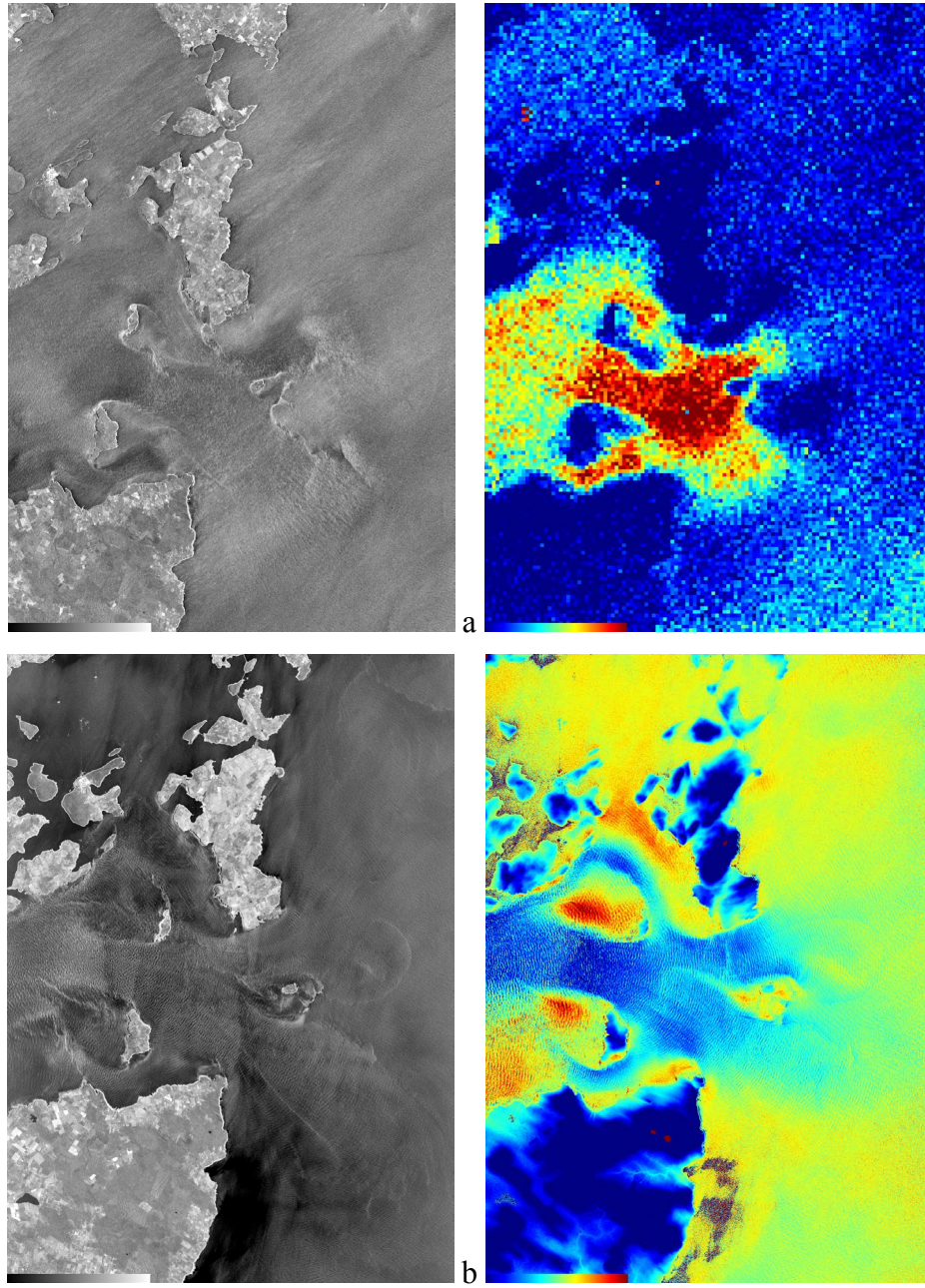


Fig. 4: Two TerraSAR-X/ TanDEM-X ATI images of the Orkney Islands (Scotland), showing image intensities (20dB range) on the left and horizontal Doppler velocities (4 m/s range) on the right. The scene size is approx. $30.0 \text{ km} \times 42.5 \text{ km}$. The upper image (a) was acquired by TerraSAR-X in DRA mode on 26 April 2010. Even with averaging over $100 \text{ m} \times 100 \text{ m}$ grid cells, the Doppler velocity is very noisy and would require further averaging / smoothing to obtain a smooth current field. The lower image (b) was acquired by TerraSAR-X and TanDEM-X with an effective along-track baseline of 25 m. With this near-optimal baseline, the data quality is so good that the orbital motions of long surface waves are resolved after averaging over $25 \text{ m} \times 25 \text{ m}$ grid cells. Further analysis has shown that the ATI-derived current fields are in good agreement with results of a numerical circulation model of the area.